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# Improving dynamic soil parameters and advancing the pile signal matching technique

Kam Weng Ng [a,*], Sri Sritharan [b]

[a] Department of Civil and Architectural Engineering, University of Wyoming, Laramie, WY 82071, USA
[b] Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA 50011, USA

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ABSTRACT

The pile signal matching technique widely used for estimating vertical resistances of piles during construction is highly influenced by the assumed dynamic soil parameters. Due to the lack of understanding and supporting data, constant soil parameters for the entire pile length have been routinely used. This practice is unrealistic and compromises the signal match quality. Using recently completed field tests, this paper develops empirical equations for dynamic soil parameters in terms of measureable soil properties and proposes an improved signal matching technique, thereby allowing for better match quality.
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## 1. Introduction

A challenge associated with driven pile foundations is the ability to accurately verify pile resistance at the end of driving (EOD) so that they can be constructed cost-effectively. Pile resistance in the field is verified using expensive and time-consuming static load tests, less efficient dynamic driving formulas that typically produce unnecessarily conservative results [1], or reliable and cost-effective dynamic analysis methods [2]. For this reason, dynamic analysis methods, such as the CAse Pile Wave Analysis Program (CAPWAP), developed by Rausche et al. [2], have been widely used as the construction control method for pile driving. However, the accuracy of dynamic analysis methods is highly influenced by dynamic soil parameters, in which unrealistic constant values for the entire pile length have been routinely used. To improve the reliability of dynamic analysis methods, this paper focuses on quantifying more realistic dynamic soil parameters as a function of soil types and properties.

Pile resistance verification using CAPWAP is performed by matching the measured pile force and velocity signals collected from a Pile Driving Analyzer (PDA) with the corresponding signals simulated based on one-dimensional soil–pile model proposed by Smith [3], as shown in Fig. 1. In this model, a pile is represented by a series of masses ($m$) connected with elastic–plastic springs representing the pile stiffness while the surrounding soil is represented by a series of linear-plastic springs and linear dampers. The accuracy of pile resistance verification using CAPWAP based on this model is highly dependent upon the proper selection of two dynamic soil parameters, i.e., quake value ($q$) that defines the soil stiffness ($k$) represented by a linear-plastic spring, and damping factor ($J$) that determines the viscous damping coefficient ($c$) represented by a linear damper [4]. Although varying soil types with different soil properties typically exist along a pile, constant shaft quake ($q_s$) and shaft damping factor ($J_s$) are currently used in CAPWAP analysis to define the soil characteristics along the pile shaft [4]. Similar to the dynamic shaft parameters, constant toe quake value ($q_T$) and toe damping factor ($J_T$) are also used [4].

To describe the soil-damping characteristic along a pile and at pile toe, Smith [3] estimated the damping coefficient ($c$) as a product of a static soil resistance ($R_s$ along the pile shaft or $R_T$ at pile toe), a damping factor ($J$), and an instantaneous pile velocity ($v$). Since the static soil resistance describes the geostatic mode of the pile–soil system and the pile velocity is measured using PDA, the damping characteristic of the surrounding soils can be reasonably related to the damping factor.

Due to limited dynamic data for correlation studies, Smith [3] recommended constant dynamic parameters for the entire pile length embedded in any soil type as detailed in Table 1. Approximately a decade later, Coyle et al. [5] estimated a set of dynamic parameters for three different soil types (i.e., clay, sand, and silt) from full-scale pile load tests. Compared with Smith's

* Corresponding author. Tel.: +1 307 766 4388; fax: +1 307 766 2221.
*E-mail address:* kng1@uwyo.edu (K.W. Ng).

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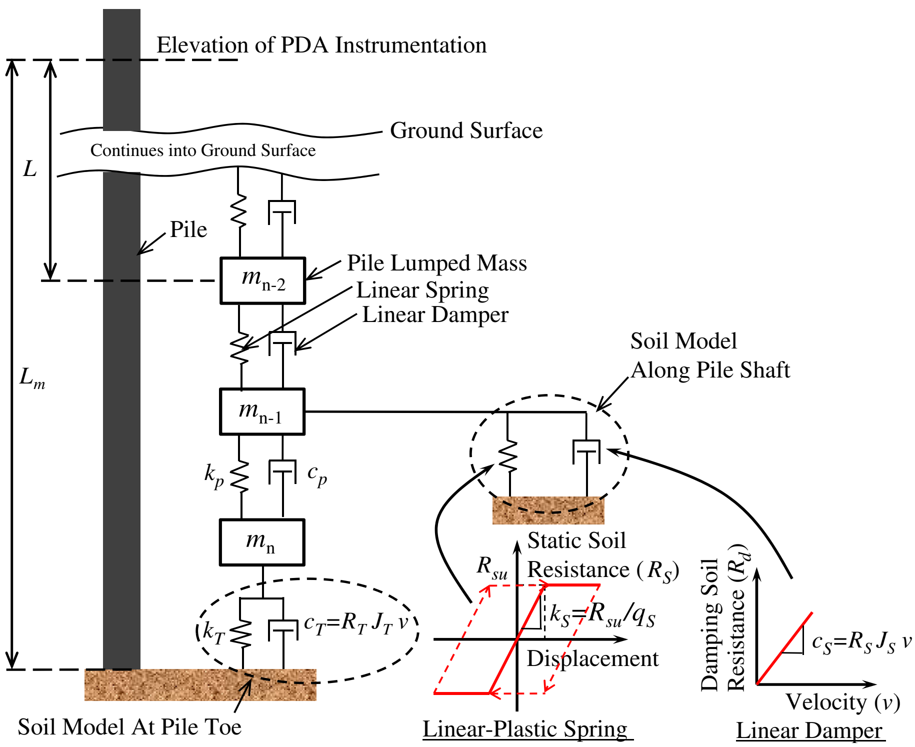


**Fig. 1.** One-dimensional soil–pile model (adapted after Pile Dynamics Inc. [4]).

**Table 1**
Summary of previously suggested dynamic soil parameters.

| Reference | Damping factor (s/m) | | Quake value (mm) | |
|---|---|---|---|---|
| | Shaft ($J_s$) | Toe ($J_T$) | Shaft ($q_s$) | Toe ($q_T$) |
| Smith [3] | 0.16 | 0.49 | 2.54 | 2.54 |
| Coyle et al. [5] | 0.66 for clay<br>0.16 for sand<br>0.33 for silt | 0.03 for clay<br>0.49 for sand<br>0.49 for silt | 2.54 | 2.54 |
| Hannigan et al. [6] | 0.66 for cohesive soil<br>0.16 for non-cohesive soil | 0.49 | 2.54 | $D$/120 for dense and hard soil<br>$D$/60 for soft soil |

$D$ – pile diameter/width.

recommendations, Coyle et al. [5] proposed as much as two to four times higher shaft damping factors for silt and clay and a negligibly small toe damping factor for clay, which suggest that dynamic soil parameters are not constant but dependent on soil types. These authors acknowledged that an extensive data set was not available at the time for characterizing the dynamic parameters and therefore suggested the use of more accurate parameters, if available, in the future. In the absence of further refinements to dynamic soil parameters, Hannigan et al. [6] adopted recommendations of Coyle et al. [5] with an adjustment for the toe quake value in terms of pile diameter/width ($D$). Hannigan et al. [6] believed that damping factors are not constant for a given soil type, and a higher value may be more appropriate for soft soils than hard rock. Based on their accumulated pile driving experience and observations, Hannigan et al. [6] noted that damping factors should also be expected to vary with time after the EOD, and higher dynamic parameters may be appropriate for the analyses modeling the beginning of restrike (BOR) condition. However, due to the lack of dynamic pile measurements and quantitative analyses, their hypotheses have not been validated, and constant parameters as listed in Table 1 have been used for dynamic analyses.

Based on a series of dynamic load tests on a 61-mm diameter steel, smooth, close-ended pipe pile driven in a fine to medium poorly grade sand, compacted to three different relative densities of 35%, 50% and 70%, Malkawi and Ayasrah [7] concluded that damping factors ($J$) are inversely proportional to sand relative density and static sand resistance. Nonetheless, relationships between dynamic soil parameters and measureable soil properties were not established due to the lack of extensive dynamic measurements and good quality data sets.

Liang [8] conducted a statistical analysis on the dynamic soil parameters using a database of 611 driven piles collected by Paikowsky et al. [9]. The dynamic soil parameters summarized in Table 2 were estimated by Liang using the routine CAPWAP signal matching procedure, in which constant dynamic soil parameters were used for the entire subsurface. Considering two soil types (i.e., sand and clay) and when the dynamic pile testing was performed (i.e., EOD and BOR), Table 2 reveals that the quake values varied minimally with the soil type and schedule of dynamic testing, while the damping factors were found to be influenced more by when the dynamic testing was done rather than the soil type. The relatively high standard deviation indicated a large scatter in

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